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A Cross-Language Study of Voicing Contrasts of Stops

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1. INTRODUCTION

Voicing contrasts of stops have been one of the major topics in phonetics and phonology, and have been examined for a number of languages. Through a number of experimental studies, it can be said that their articulatory and acoustic bases are now fairly well understood, though the details of some specific aspects of individual languages remain to be clarified. It is now understood what acoustic and physiological features are relevant for the distinction between voiceless and voiced sounds in major languages. It is also known that there are some cross-language differences in these features and the "same" voicing categories show some differences in their phonetic realizations. There are many examples which show cross-language differences in the voicing contrasts of stops. For instance, voiced stops /b, d, g/ in English are phonetically realized as "voiceless" unaspirated stops [b̥, d̥, g̊] in the word-initial position, and these realized forms are different from the counterparts of voiced stops in French. Moreover, it is often noticed that foreign language learners sometimes have to adjust the voice settings in learning foreign languages, since there is a difference in voicing characteristics between mother and target languages. There have been some efforts to study how the language-specific properties for the voicing categories differ from each other and how the differences are specified in terms of phonetic features (Lisker and Abramson, 1964 ; Keating et al., 1983 ; Dixit, 1987). One of the significant contributions in these cross-language studies of voicing contrasts of stops is Lisker and Abramson (1964). They examined the voicing categories of eleven languages to see how voice onset time (VOT) serves to separate the stop categories. They classified these languages into three category groups, depending on phonological contrast they use : (1) two-category languages, (2) three-category languages, and (3) four-category languages. They measured the VOT values in the initial stops in these languages, and found that the stop categories generally fall into three ranges and the categories are distributed in the ranges centering at -100, $+10$ and $+75$ ms. The present study is a further attempt to examine some cross-language differences and similarities among the voicing contrasts of stops in five Asian languages : Japanese, Korean, Burmese, Thai, and Hindi. Specifically, how do the language-

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specific properties of voicing categories of stops differ from one another in these languages? If different, how are they different and how is the variation represented? The languages under investigation are divided into three types according to the above classification. Japanese is a two-category language, while Korean, Burmese and Thai are three-category languages. Hindi, as in other Indo-Aryan languages, is a four-category language. These languages were selected since they provide the examples of several types of voicing categories of stops and their voicing contrasts involve several modes of vocal-folds adjustments.

2. METHODS

2. 1. Languages and Subjects

Linguistic materials for analysis consist of minimal or near minimal contrasts of monosyllabic words in each language. Speakers of five different languages were recorded saying monosyllabic words in which initial consonant differs. The following list indicates the languages investigated, their voicing categories of stops, and the number subjects.

Language	Voicing Category	No. of Subject
Japanese	voiced stops /b, d, g/	3
	voiceless stops /p, t, k/	
Korean	voiceless tense unaspirated stops /p*, t*, k*/	3
	voiceless lax unaspirated stops /p, t, k/	
	voiceless aspirated stops /pʰ, tʰ, kʰ/	
Burmese	voiced stops /b, d, g/	1
	voiceless unaspirated stops /p, t, k/	
	voiceless aspirated stops /pʰ, tʰ, kʰ/	
Thai	voiced stops /b, d/	2
	voiceless unaspirated stops /p, t, k/	
	voiceless aspirated stops /pʰ, tʰ, kʰ/	
Hindi	voiced stops /b, d̪, g/	3
	breathy stops /bʰ, d̪ʰ, gʰ/	
	voiceless unaspirated stops /p, t̪, k/	
	voiceless aspirated stops /pʰ, t̪ʰ, kʰ/	

2. 2. Acoustic Analysis

Acoustic analysis of the recorded materials was made through the ILS software package and KAY Sonagraph 7800 in the Phonetics Laboratory, University of Edinburgh. Recorded materials were, after 5 kHz low-pass filtering, digitized at a sampling rate of 10 kHz. The digitized materials were stored for reviewing and listening in a sampled file, and were analyzed at 50 points per frame by the autoregressive linear prediction and Fo extraction. At each point, Fo frequencies, formant frequencies, bandwidths, and amplitudes for the lower three formants were obtained. The durational measurements were made by manually positioning two cursors in the display of waveforms. Furthermore, energy spectra were sampled in the short time period (30 ms) immediately following the stop release to examine the spectral characteristics. For some of the utterances, wide-band spectrograms were prepared for identifying some of the ILS outputs.

3. Results

3. 1. Voice Onset Time (VOT)

Voice onset time (VOT) is defined as the time interval between the release of the oral release and the onset of voicing, and has been considered as one of the major acoustic dimensions for the voicing differences. Table 1 presents the mean VOT values and ranges of stop consonants in each language.

Table 1 Mean VOT and range (msec) of stops in Japanese, Korean, Burmese, Thai and Hindi

Japanese

	VOT	Range		VOT	Range
/b/	−72	(−45 — −95)	/p/	44	(15 — 60)
/d/	−58	(−10 — −70)	/t/	27	(15 — 90)
/g/	−64	(−20 — −105)	/k/	68	(45 — 100)

(N=27 for bilabials and alveloars, 45 for velars)

Korean

	VOT	Range		VOT	Range		VOT	Range
/p*/	10	(0 — 30)	/p/	31	(20 — 40)	/pʰ/	86	(75 — 95)
/t*/	11	(5 — 20)	/t/	20	(15 — 25)	/tʰ/	85	(75 — 105)
/k*/	23	(15 — 40)	/k/	49	(20 — 70)	/kʰ/	96	(85 — 110)

(N=24 for tense, 12 for lax and aspirated)

Burmese

	VOT	Range		VOT	Range		VOT	Range
/b/	−104	(−90 — −120)	/p/	3	(0 — 10)	/pʰ/	46	(35 — 70)
/d/	−106	(−85 — −125)	/t/	15	(10 — 25)	/tʰ/	67	(55 — 85)
/g/	…		/k/	31	(30 — 35)	/kʰ/	76	(55 — 95)

(N=6 for bilabials, alveolars, and velars)
… data was not obtained.

Thai

	VOT	Range		VOT	Range		VOT	Range
/b/	—104	(−85 — −120)	/p/	5	(5 — 10)	/pʰ/	73	(50 — 95)
/d/	−106	(−70 — −140)	/t/	8	(5 — 10)	/tʰ/	76	(65 — 95)
			/k/	23	(15 — 30)	/kʰ/	95	(85 — 105)

(N=12 for bilabials, alveolars, and velars)

Hindi

	VOT	Range		VOT	Range		VOT	Range		VOT	Range
/b/	−96	(−50 — −110)	/bʰ/	−91	(−60 — −120)	/p/	12	(15 — 20)	/pʰ/	75	(50 — 90)
/d̪/	−108	(−85 — −125)	/d̪ʰ/	−88	(−60 — −110)	/t̪/	12	(10 — 15)	/t̪ʰ/	82	(60 — 100)
/g/	−121	(−95 — −140)	/gʰ/	−105	(−65 — −120)	/k/	34	(25 — 40)	/kʰ/	119	(110 — 125)

(N=9 for bilabials, dentals, and velars)

As is seen in Table 1, there is a clear difference in VOT between the voicing categories in Japanese, Burmese and Thai. In these languages, VOT serves to make a distinction between the categories. But in languages such as Korean and Hindi, there is an overlap in the range of VOT between the tense and lax stops in Korean and between the two voiced stops in Hindi. These overlaps are also pointed out by other investigators (Han and Weitzman, 1970; Benguerel and Bhatia, 1980) and this indicates that VOT is not functional for distinguishing between these voicing categories in these two languages. It can also be seen that Japanese which has two-voicing categories shows a relatively wide range of variation in each category.

As to the VOT value in relation to place to articulation, it can be seen that for voiceless categories the value is greater for velar stops than for bilabial or alveolar stops, though this tendency is not evident in the voiced categories. This tendency is often found in other languages such as English and may be attributed to a smaller supralaryngeal cavity behind the constriction for velar stops, resulting in the delayed onset of voicing.

In order to examine the cross-language differences of voicing contrasts of stops, analysis of variance (ANOVA) was performed on the VOT values in these languages. The VOT values of each category were "standardized" (averaged) for different phonetic environments and different subjects in each language. For each phonetic category which is transcribed by the same phonetic symbols, a one-way ANOVA was applied to examine the language effect. The results can be shown as follows:

Table 2 ANOVA Results: Language Effect on VOT in Five Languages

Segment	df	F ratio	Significance
/p/	$F(4, 45)$	20.99	$p<.01$
/t/	$F(4, 45)$	14.78	$p<.01$
/k/	$F(4, 45)$	12.79	$p<.01$
/b/	$F(3, 36)$	3.05	n. s.
/d/	$F(3, 36)$	4.34	n. s.[1]
/p^h/	$F(3, 36)$	1.09	n. s.
/t^h/	$F(3, 36)$	1.34	n. s.
/k^h/	$F(3, 36)$	3.38	n. s.

As shown in Table 2, stops /p, t, k/ in ANOVA yielded considerable differences among languages and the proportion of variance is significant. For aspirated stops, however, the F ratios are small and there is no significant variance across the languages. For voiced stops, there is a variance greater than those of aspirated stops, but the proportion of variance is still not significant. The ANOVA results indicate that in the production of aspirated stops, there is no significant difference across languages in the laryngeal timing events to oral release and they are articulated in the similar timing events in these languages. On the other hand, there is a great deal of variance in the production of voiceless unaspirated stops /p, t, k/ across languages, and this indicates that there is a wide range of timing domains for producing these stops in these languages. The data on VOT values show that stops /p, t, k/ in Burmese and Thai are articulated in a rather narrow timing range, while those in Japanese are in a wide timing range.

3. 2. Fundamental Frequency (Fo)

It is known that voicing contrasts are closely related to pitch perturbations in the following vowels. Voiceless stops tend to be associated with a high pitch range, and voiced stops with a low pitch range. The difference of pitch range is considered to be one of the properties for a voiced-voiceless distinction. In the present study, the measurements of Fo were made at the vowel onset following a stop release. Table 3 presents a pooled mean for major voicing categories in each language.

Table 3 Mean Fo for major categories at vowel onset (Hz)
(s. d. in parenthesis)

Language	Major Category	Fo(in Hz)
Japanese	voiced stops	213.8 (6.2)
	voiceless stops	248.5 (19.5)
Korean	voiceless tense stops	175.1 (16.7)
	voiceless lax stops	141.2 (30.5)
	voiceless aspirated stops	180.8 (24.6)
Burmese	voiced stops	167.0 (6.9)
	voiceless unaspirated stops	187.7 (5.0)
	voiceless aspirated stops	186.8 (6.6)
Thai	voiced stops	183.5 (14.0)
	voiceless unaspirated stops	186.0 (9.9)
	voiceless aspirated stops	205.1 (14.2)
Hindi	voiced stops	115.7 (19.2)
	breathy stops	108.0 (14.7)
	voiceless unaspirated stops	130.4 (27.6)
	voiceless aspirated stops	125.2 (28.8)

There are several points on the Fo data that should be noted. First, it can be seen as a general trend that Fo following voiceless stops and voiceless aspirated stops are considerably higher than those following voiced ones. In Thai, however, there is no significant difference in Fo value between voiced unaspirated stops and voiceless unaspirated stops (two-tailed t-value=0.46, n. s.). Second, voiceless tense stops in Korean show a higher Fo than voiceless lax stops. This implies that there is a difference in the initial glottal state between the two stops. According to Hirose et al. (1974), it is pointed out that there is a sharp increase in the activity of thyroarytenoid for voiceless tense stops. Third, the Fo of breathy stops

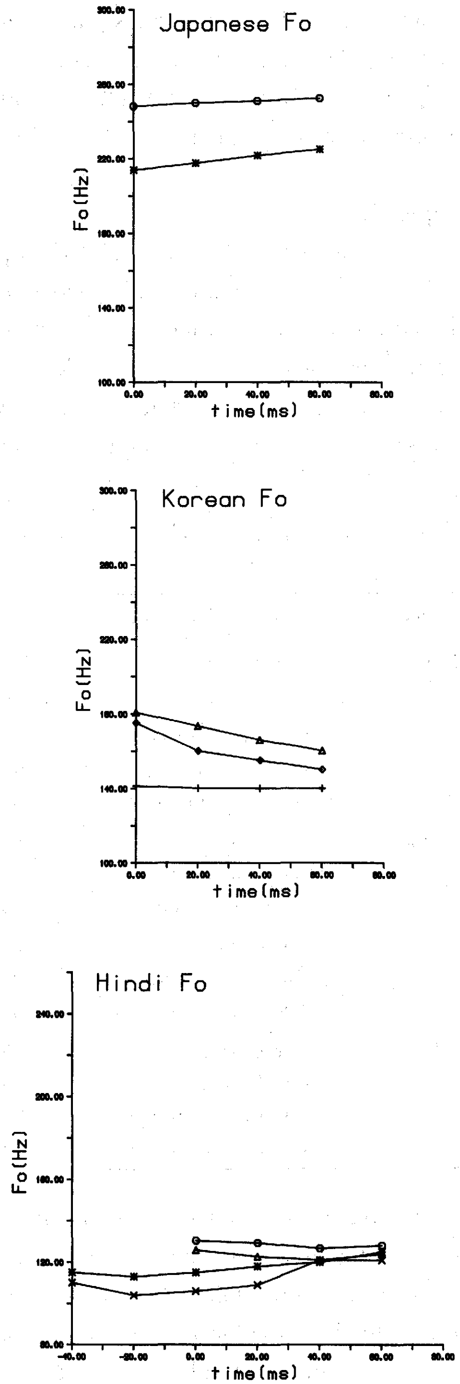


Fig. 1. Schematized Fo curves of stops in Japanese, Korean and Hindi[2]

Japanese(top) voiced ✳ voiceless ○

Korean(middle) tense ◇ lax + aspirated △

Hindi(bottom) voiced✳ breathy × voiceless ○ aspirated △

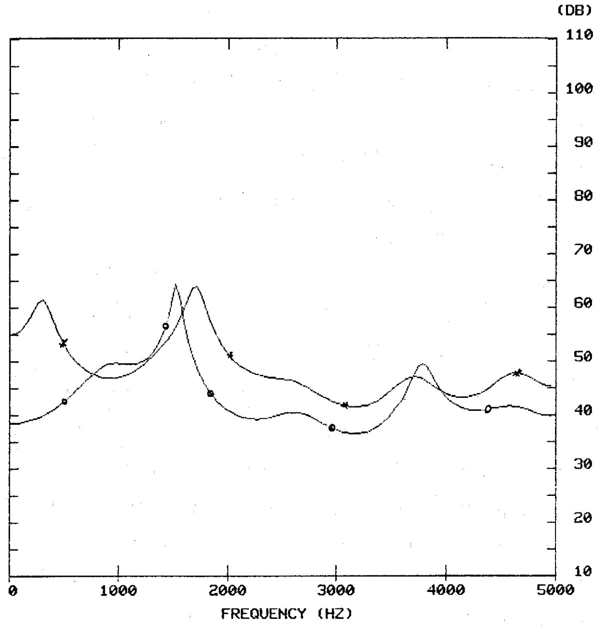
in Hindi is the lowest among the four categories of stops, and it can be presumed that this is caused by suppression of vocal folds vibration due to a change of glottal apperture.

Associated with the differences in the onset Fo values, it is known that there is also a difference in the Fo curves from the onset of vowel to the steady-state portion of vowels, as discussed by Hombert (1978). In the present study the Fo curves were examined for the period of 50 to 60 ms after vowel onset. Figure 1 shows the schematized Fo curves for the vowels following the major voicing categories in Japanese, Korean, and Hindi. Burmese and Thai were excluded since they are tonal contrast languages, and it is not easy to minimize the effect of tone on the intrinsic Fo curve. From the examination in Figure 1, it is seen that the Fo curves following the voiced stops in Japanese and Hindi give rise and show a gradual rising pattern, while the voiceless aspirated stops in Korean and Hindi show a gradual falling pattern in the same period. For voiceless unaspiratd stops, the curve in Japanese shows a slight rising pattern within 50 to 60 ms, while the one in Hindi shows a steady falling. Furthermore, the Fo curve of voiceless tense stop in Korean shows an abrupt drop immediately after vowel onset The Fo curve of breathy stops in Hindi shows a steady falling during closure, and upon release gradually goes up. This fall-rise pattern of Fo seems to be characteristic for breathy stops. Although the voiced stops in Hindi show a similar direction of change, the ones of breathy stops are more distinctive and pronounced than those of voiced stops.

3. 3. Spectral Analysis

It is generally considered that there is a difference in the articulatory force at the time of consonantal release between voiced and voiceless categories. In the present study, the short-time spectra were sampled by ILS linear prediction for the initial period of 30 ms immediately after the consonantal release. This period includes both the burst and some portion of the voicing onset. In the case of voiced stops, this period includes the burst and some portion of the vowel onset, whereas in the case of voiceless stops, this includes mainly the burst and some portion of aspiration, and it does not extend to vowel onset. Although this period is considered to contain some invariant cues for place of articulation (Blumstein and Stevens, 1979), the present study mainly examined the intensity and spectral characteristics. The power spectra and smoothed ones were sampled for most of the tokens in each language and some of the examples of smoothed power spectra are presented in Figure 2.

Although spectral characteristics are rather difficult to quantify, the examination of power spectra in each language reveals some differences in intensity level and spectral characteristics. For Japanese, it can be noted that the intensity level of voiceless stops is slightly higher than that of voiced stops, but the difference is



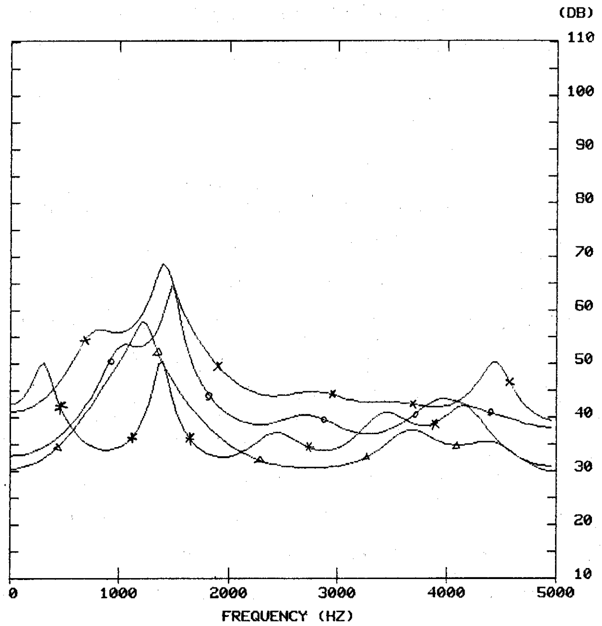


Fig. 2. Examples of power spectra sampled at the time window (30 ms) after release of Japanese (top) and Hindi (bottom) stops

Japanese [ga]⁎ [ka] ○

Hindi [gan] ⁎ [g^han] × [kan]○ [k^han] △

not consistent in some tokens. Therefore, the difference in the overall intensity level does not appear to be major acoustic dimension for the voicing differences. Although the difference in the intensity level is not consistent, there is a small but noticeable difference in spectral shape between the two voicing categories. There is a spectral peak in the low frequency region for the voiced stops, but not in voiceless ones.

For Korean stops, the power spectra indicate that the intensity of aspirated stops is considerably higher than those of other types of stops. Although it is pointed out that there is a difference in the time to build-up intensity ; a shorter rise time for tense stops than for other stops, the results in the present study did not show a noticeable difference between the three voicing categories (Han and Weitzman, 1970).

For Burmese stops, the power spectra showed that there is a difference in the overall intensity between voiced and voiceless stops ; the intensity for voiceless stops is relatively higher than it is for voiced stops, but there is no marked difference between the two voiceless stops.

For Thai stops, the voiceless aspirated stops are clearly separated from other two voicing categories ; the voiceless aspirated ones show less intensity level and energy peaks are less regularly distributed, while in voiced stops and voiceless unaspirated stops, energy peaks are apparent and regularly distributed.

For Hindi stops, there is a marked difference between the two voiced categories. The intensity level of breathy stops is greater than that of voiced unaspirated stops. There is also a difference in the spectral shape which should be noted. As seen in Japanese, the voiced unaspirated stops show a peak in the low frequency region, but other types of stops do not.

4. Discussion

The acoustic results given above indicate that there are some differences in characterizing the voicing categories of stops in the five languages, and there are also some similarities shared by the same categories in these languages. The use of each acoustic dimension for voicing distinction is summarized in Table 4. A slash in Table 4 indicates that the voicing categories are separated by the acoustic feature, and a dotted slash indicates a weak tendency of separation.

Voice onset time (VOT) is an efficient dimension for distinguishing voicing differences in Japanese, Burmese and Thai. In these languages, there is a clearcut difference for the voicing categories. As seen in the range of VOT, Japanese shows a rather wide variability of VOT for each category, while voiceless unaspirated stops in Burmese and Thai show a restricted range of VOT variation. It can also be found that Burmese aspirated stops show a medium range of voicing delay, compared to those in Korean and Hindi. As pointed out in earlier studies

Table 4 The use of acoustic features which differentiate the voicing categories in five languages

Acoust. Feature	Japanese	Korean	Burmese	Thai	Hindi
VOT	Vd/Vl	T L/Asp	Vd/Vl/Asp	VD/VL/Asp	B Vd/Unasp/Asp
Fo at vowel onset	Vd/Vl	L/T Asp	Vd Vl/Asp	VD VL/Asp	B Vd/Unasp Asp
Fo curve	Vd/Vl	L/T/Asp	—	VD/Vl Asp	B/Vd/Unasp Asp
Intensity	—	L/T Asp	Vd/Vl Asp	Vd Vl/Asp	B Vd/Unasp Asp

(Vd=voiced, Vl =voiceless, T=voiceless tense
L=voiceless lax, Asp=voiceless aspirated, Unasp=voiceless
unaspirated, B=breathy)

(Han and Weitzman, 1970 ; Benguerel and Bhatia, 1980), VOT is not sufficient to separate the voicing categories from each other in Korean and Hindi, and there should be other additional dimensions to characterize them. VOT is known to represent a timing relationship relative to oral release. So VOT serves to separate the categories from each other if the voicing distinction is based on the laryngeal timing events, but if the voicing categories involve other laryngeal features such as glottal tension as in Korean and glottal gesture as in Hindi, several other acoustic dimensions are needed for distinction.

Furthermore, as is known, the relative timing of laryngeal and supralaryngeal events is important in distinguishing the voicing categories. As mentioned above, there are three timing domains for major voicing categories, and among these domains, the one for voiceless unaspirated stops appears to show language specific timing events and a variable domain across languages. For instance, /p, t, k/ in Japanese show a wide range of timing domains, while those in Thai and Burmese show a rather limited range. Some languages such as Korean and Hindi use other laryngeal features than timing relation for the voicing distinction, and it appears that the such features are incorporated or "added" within the domain of the timing continuum which is for voiceless unaspirated stops. On the other hand, voiceless aspirated stops show little variance in range of timing among languages. In my view this is because aspiration requires a wide open glottis, timing adjustment between oral release and peak glottal opening, and sufficient airflow. Thus there seems to be little flexibility in the timing event in the production mechanism of aspiration.

The Fo data indicate that the frequency at vowel onset is relatively higher in the voiceless stops than in the voiced stops. The Fo curves are rising for the voiced categories, while the ones for the voiceless ones are level or falling. The voiceless aspirated stops show an initially high and then a gradual falling pattern. There are several points to note on the Fo and its curves. First, the Fo curves of the voiceless tense stops in Korean begin in higher range and abruptly fall within a period of 30 ms after the vowel onset. Physiological studies made by Hirose et al. (1974) indicate that there is a sharp increase in the activity of thyroarytenoid, and this increase of tension is considered to be responsible for abrupt movement of the Fo. Furthermore, Kagaya (1974) indicates that aspirated stops in Korean are produced with the maximally opened glottis and high airflow rate. From these studies, there appear to be two different causes for a higher Fo in tense and aspirated stops in Korean. Second, it should be noted that the Fo at breathy portion in Hindi is the lowest among the four types of stops, and the breathy stops show a distinctive fall-rise pattern of Fo. For explaining this markedly low Fo, it can be speculated that the vocal folds are vibrating without complete closure, and the vibration is suppressed by a narrow opened glottis, resulting in the low Fo at the onset. Although the influence of breathy stops on the following vowel was examined by Schiefer (1986), the pattern of fall-rise itself should be correlated with the breathy state of the glottis.

As to the spectral analysis, it is rather difficult to quantify, but it presents intriguing results for the voicing distinction. Although it is considered that the intensity level is relatively higher for the voiceless stops than it is for the voiced ones, this is not consistent in Japanese. This implies that the articulatory force should be considered not only by airflow rate, but also by the timing of glottal opening to the oral release. Furthermore, aspiration is considered to give a high intensity, and this holds true in Korean, but is not true for Hindi and Thai voiceless stops. Another point that should be noted here is that there appears to be a difference in spectral shape in the initial portion immediately after the release. As shown in Figure 2, the voiced category /g/ shows a peak in the low frequency region, but this is not present in breathy stop and voiceless stops. Although further evidence is needed, the spectral characteristics in the low frequency region may serve to signal the voiced category.

5. Conclusion

The languages in the present study use several acoustic dimensions for voicing categories in a different way, and the "same" voicing categories have a language-specific variability, as well as features which are common to them. VOT functions for distinction if the voicing categories are based on the laryngeal timing to the oral release. If other laryngeal features are involved, other dimensions are needed for distinction. Among major voicing categories, voiceless unaspirated stops show a wide range of variability in the glottal and supralaryngeal timing events, while voiceless aspirated stops do not. The Fo at the onset represents the initial state of the glottal adjustments and will be significant for characterizing the voicing categories which involve the change of initial glottal gesture as seen in Hindi breathy stops. Spectral analysis such as intensity level and spectral shape appears to provide a useful cue, and the low-frequency spectral characteristics appear to be correlated with the voicing distinction.

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NOTES

1. It is not significant at 1 % level, but significant at 5 %.
2. The zero point in Figure 1 indicates the onset of voicing, and it should be noted that the onset in the voiceless stops does not coincide with the one in real time, i. e., as shown in VOT, the voicing starts rather later in real time.

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